

Design of Glued-in-rods connections in timber structures

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RESUME Timber structures in glulam are booming in recent years. It has led to the development of high-performance connections, like glued-in-rods (GiR). Glued-in-rods are threaded rods inserted into boreholes with glue. They offer aesthetic advantages, high performance and stiffness. Lack of knowledge about this connection, whose design is not governed by the Eurocode, considerably limits their use. This study presents experimental testing on glulam beam-to-column connections using glued-in-rods and a traditional connection (metal clamp). Two configurations of GiR connection are tested, one with 2 rods, and one with 4 rods. Experimental tests show that glued-in-rods connections have greater rotational stiffness than the traditional connection. The observed failure modes of the connections were the yielding rods by tensile force. It was also concluded that capacity appears to be a function of the number of rods: doubling the number of rods doubles the capacity of the connection (rods on the same axis). The same applies to rotational stiffness. Comparison of experimental results with model predictions showed good agreement, with a deviation under 15% for the maximum tension experienced in the rods.

Mots-clefs Wood, Bio-based material, Fastening, Stiffness, Glulam timber

I. INTRODUCTION

Wood as a building material is booming over the few decades (Amaco 2016). Its use has been somewhat hampered by the emergence of modern materials such as concrete and steel. Now, with the global warming issue, wood, as a biobased material, can be a good ally (Richard 2023).

Nowadays, glued laminated timber is the most widely used. The cross-section and length of finished elements such as wide beam spans can be achieved and are no longer limited by the size of the initial component parts. The combination of wood pieces covered with glue also improve the material performances. Glued laminated timber makes it possible to obtain curved and free shapes (Trinh & Ligot 2014).

Assemblies are generally the most delicate points in timber construction. Several types of connections exist. They depend on the type of structure, the country, the know-how. This classification can be considered: *traditional connections (wood-on-wood joints)*, *steel connections* (Trinh & Ligot 2014) and now, *Glued-in-Rods connections (GiR)*.

These are recent in timber construction field, mostly in post-beam and CLT structures, with glued timbers. It consists of steel thread rods, anchored with adhesive. It could be applied to timber-to-timber, timber-to-steel & timber-to-concrete connections (Richard, 2023). Simonin, a French timber construction company which offers an approved GiR solution, presents their advantages (Simonin 2018): a good strength and stiffness, a good resistance against fire, efficient in load transfer and lightweight. They also present aesthetic qualities (no visible steel).

They are not covered from a regulatory point of view by Eurocode 5 (Eurocode 5, 2005) yet. However, in Europe some standard documents do exist: a Technical Report TR070 (TR070 2019) and a European Assessment Document EAD (EAD 130006-00-0304 Glued-in-Rods for timber connections). Based on this Regulation and Evaluation framework, some technical assessments are published such as the technical evaluation ATEc (ATEc 2019) by Simonin in France or the European Technical Assessment ETA-20/0834 (ETA 2020) for Epoxy injection mortar Hilti HIT RE500 V4.

The aim of this study is therefore to gain a better understanding of the behaviour of glued-in-rods, in the context of Ultimate Limit States (ULS) and Service Limit States (SLS) design. The study focuses on glued-in-rods in glulam structures, and in particular on the beam-to-column connection.

To do so, experimental tests were performed. Through three test campaigns, the aim is to observe the behaviour of GiR connections, in comparison with a traditional one, focusing on stiffness and failure mechanisms.

II. LITERATURE REVIEW

A glued-in-rod connection comprises two wooden elements. They are joined by glued threaded rods (GiR connection). For a beam-to-column connection, the connectors are subjected to a shear stress and a bending moment. The threaded rods are subjected to tension/compression following their position from the neutral axis. A part of the wood is also compressed.

III. EXPERIMENTAL SETUP

The aim is to analyse and compare the behaviour of beam-to-column connections, fastened with GiR or a metal clamp (traditional connection) (Fig. 4 and 5). Load-control tests were conducted by applying a point load at the top of the beam (Fig. 3). A 600 N pneumatic jack capacity was used. The displacements of the connection and the load were measured.

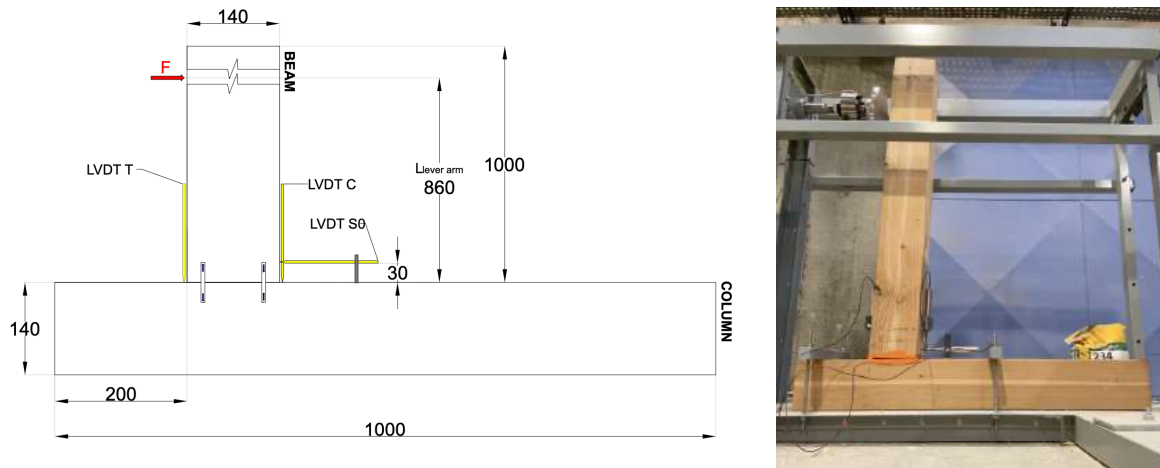


FIGURE 3. Position of the sensors and dimensions of the test

Dimensions of the specimens were chosen in accordance with Hilti HIT RE500 V4 (ETA 2020) and TR070 (TR070 2019) recommendations to avoid a wood brittle failure and to achieve a ductile failure of the threaded rod. The characteristics of the specimens are given in Table 1: these are calculation assumptions based on supplier data. GL24h is used for column and beam elements: $1\text{ m} \times 140 \times 140\text{ mm}^2$. For the connection, threaded rods (5.8), diameter of 6 mm, 120 mm length, and Epoxy HIT - RE 500 V4 are used.

TABLE 1. Mechanical properties (supplier data)

Wood properties (CTBA 2007)	Value
Shear strength $f_{v,k}$	2,7 MPa
Perpendicular compression $f_{c,90,k}$	2,7 MPa
Stiffness in tension perpendicular to grain $E_{90,g,mean}$	390 MPa

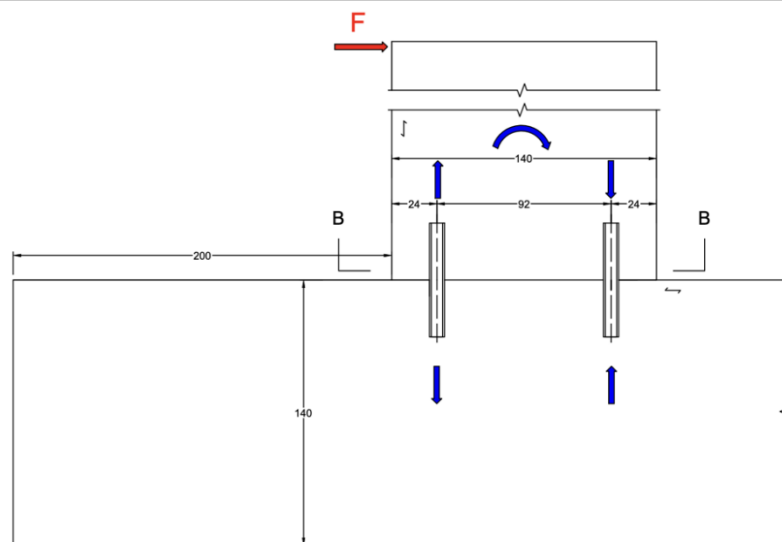
Steel properties (Eurocode 3 - NF EN 1993-1-8)	Value
Characteristic yield strength $f_{y,k}$	400 MPa
Characteristic tensile strength $f_{u,k}$	500 MPa
Young modulus	900 MPa

Adhesive properties (ETA 2020)	Value
Characteristic bond line strength $f_{vr,k}$	4,3 MPa

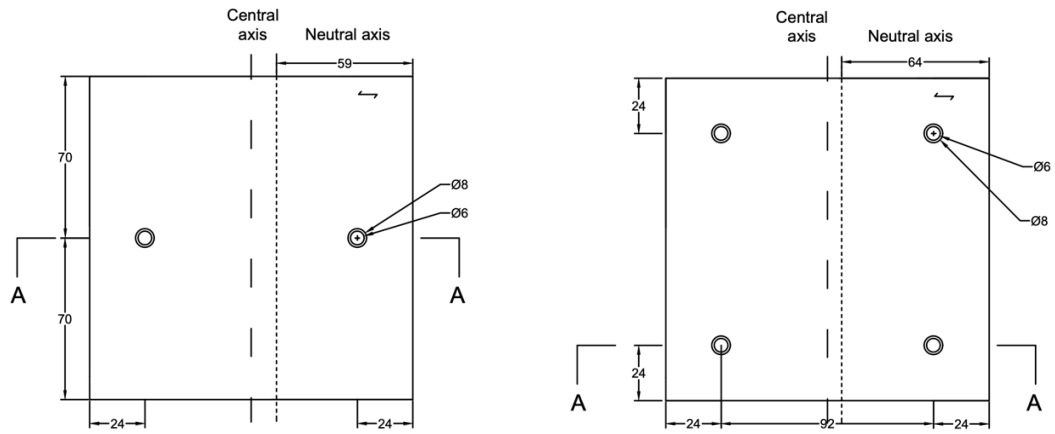
Three setups are studied: NG-2, with 2 rods; NG-4 with 4 rods and TC (Fig. 4 and 5), the traditional connection by metal clamp. Three samples of each setup are tested.

For glued-in-rods assembly, the following protocol was followed:

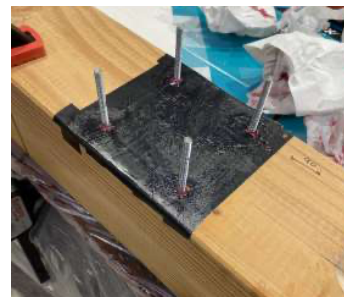
1. Drill straight with the pre-drilled diameter, slightly longer than the anchorage length.
2. Make sure the hole is clean and free of excess material, using a compressed air blower or a vacuum cleaner (ETA-20/0834 2020).
3. Tape the surfaces of wood in contact. During assembly, excess adhesive in the glued-in-rods holes is likely to overflow and glue the wood sections together. To avoid this, adhesive tape has been added between the wood sections to prevent wood-wood bonding (Fig. 4).
4. Inject the adhesive. Insert the steel rod in column: It has to be done during the adhesive's working time (maximum 12 min). Turn the rod (prEN 1995-3).
5. Insert the beam on the remaining part of the steel rod. Remove the excess adhesive carefully to avoid wood-wood bonding.
6. Clamp the assembly to hold it in place during drying (Gauthier-Turcotte & al. 2022). Make sure the assembly is perpendicular. Waiting for at least 4,5h: the curing time established the bond between rod/adhesive and timber/adhesive.



(a) Cross sectional view AA [mm] (NG-2 and NG-4)



(b) Cross sectional view BB [mm] - NG-2



(c) Cross sectional view BB [mm] - NG-4

FIGURE 4. Glued-in-rods connections (NG-2 and NG-4)

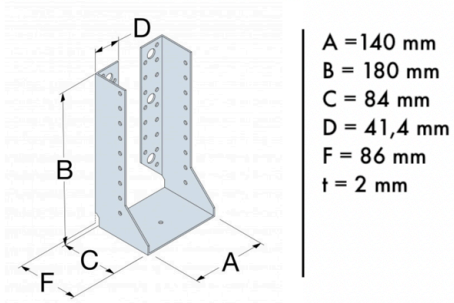


FIGURE 5. Traditional connection (TC): Metal clap (CECOIA 2023) and grooved spikes

The loading procedure is derived from an AFNOR standard (AFNOR 1991), based on an estimated theoretical value, corresponding to the theoretical maximum force. It consists of three successive phases: a precharge for the stiffness cycle and a strength test, with an acquisition rate of 10 Hz. The loading is increasing until the failure of rod or a lifting at the level of the connection higher than 11 mm.

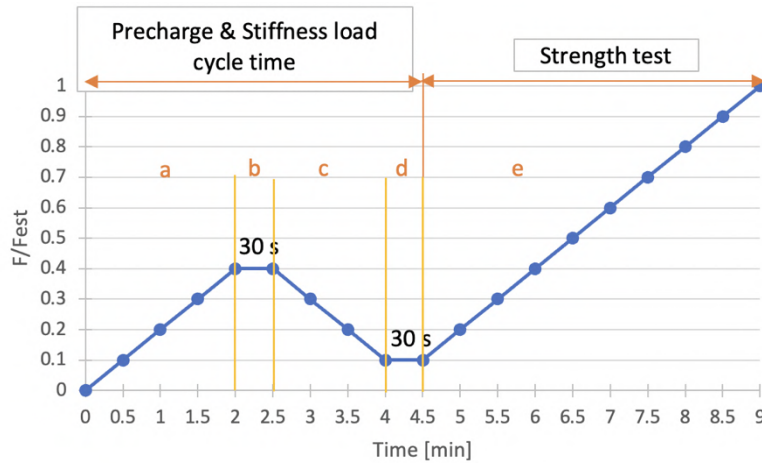


FIGURE 6. Loading procedure adapted from (AFNOR 1991)

Three LVDT sensors (Fig. 3) are used to determine the rotation θ of the joint and the slip δS between the column and the beam. LVDT T and C are used to measure, respectively, the lifting δT and the sinking δC , to deduce the rotation θ between the beam and the column. LVDT S0 is used to measure the slip $\delta S0$ between the beam and the column.

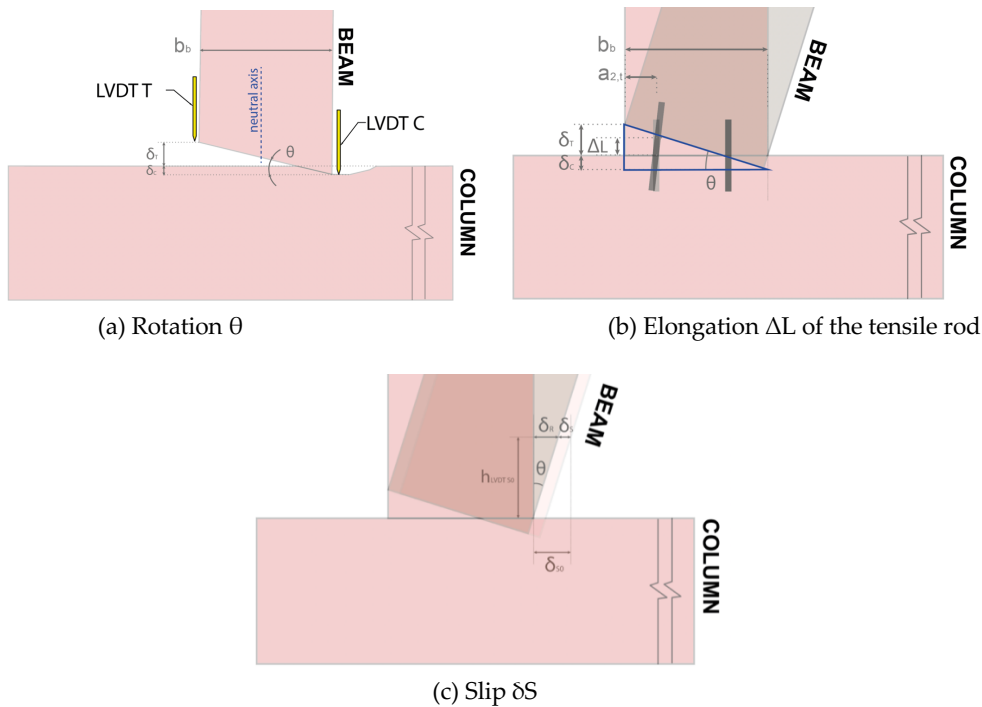


FIGURE 7. Data processing

IV. RESULTS AND DISCUSSION

A. Failure behaviour

The TC samples did not break, but their lifting δT reached the maximum criteria of 11 mm (max. lifting permitted by the dimensions and the jack): the screws were pulled out and the metal clamp was yielding. For NG-2 and NG-4, the failure is caused by the yielding rod(s) in tension. It is a ductile failure, which is much preferred to a brittle failure.

The maximal failure load is achieved for test NG-4 with an average value of 2707 N.m (Table 2). Configuration NG-4 is twice as strong as configuration NG-2 (1220 N.m). The failure values theoretically predicted by the Eurocode are twice as low. The traditional configuration (TC) has a test stopping bending moment three times lower than for NG-4.



(a) NG-2: ductile failure



(b) NG-4: ductile failure



(c) TC: Yielding of the metal clamp and pull-out of the screws

FIGURE 8. Failure mode

TABLE 2. Overview of values

(a) Experimental results

	NG-2	NG-4	TC
Failure mode	Failure of the tensile rod		Maximum permissible lifting
Max. Force F_{\max} [N]*	1410 ± 66	3130 ± 233	-
Max. Bending Moment M_{\max} [N.m]*	1220 ± 57	2707 ± 201	810 ± 43
Stiffness k_0 [kN.m/rad]*	167 ± 16	284 ± 41	19 ± 2
Plastic Angle [°]	0,4	0,3	> 4,5

*Mean ± Standard deviation

(b) Analytical results

	NG-2	NG-4	TC
Bending Moment Eurocode Characteristic capacity [N.m]	687	1375	-

The pure slip δS is given in Eq. 2 (Fig. 7c):

$$\delta S = \delta S_0 - \sin(\theta) \cdot h_{LVDTS0} \quad (2)$$

where:

- δS_0 : slip measured by the sensor (rotational slip and pure slip between the beam and the column)
- $h_{LVDT S_0}$: position of the LVDT S0

Fig. 9 gives the bending moment-slip for the three configurations. The slip of the three configurations is negligible with a maximum value of the 0,074 mm for GiR connections and 0,161 mm for TC connections.

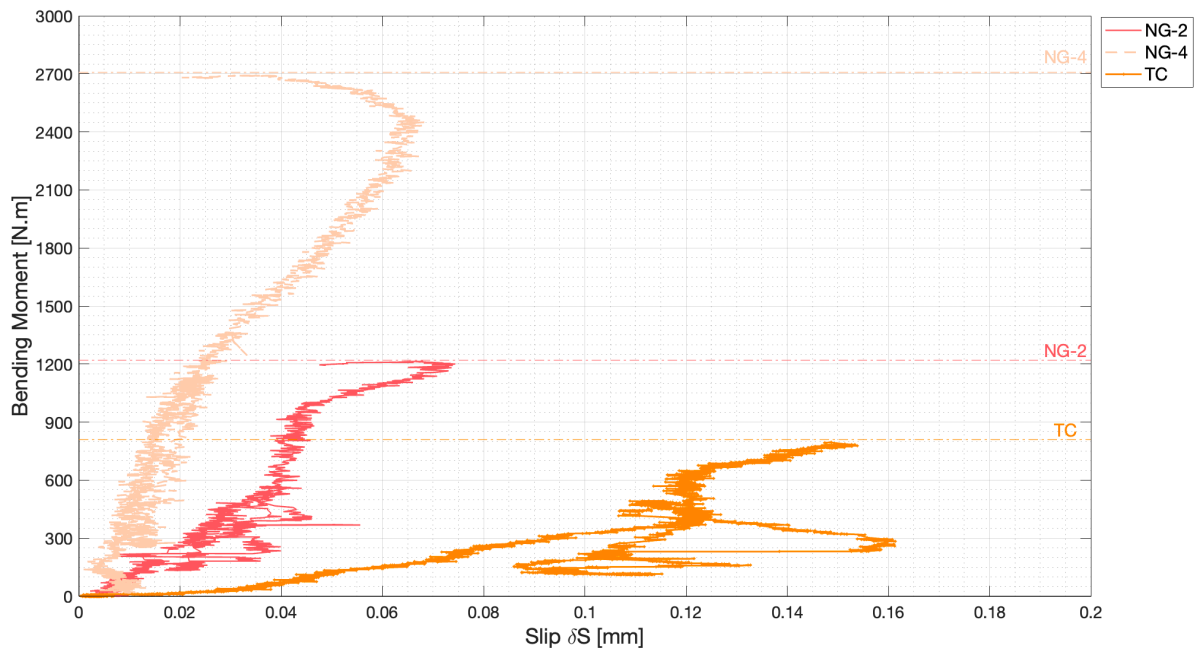


FIGURE 9. Bending Moment VS Slip

B. Elastic behaviour

Fig. 11 gives the bending moment-displacement for the three configurations. For each series, lifting was two to three times greater than sinking. The sinking occurs as a result of rods and wood compression. Lifting, on the other hand, is only induced by rod tension. Moreover, the neutral axis is not in the middle of the connection.

TC offers the greatest displacements (30 times more than for configurations with GiRs). The maximum lifting criteria, i.e. $\delta T > 11\text{mm}$, is only reached by the TC series, bringing the test to an end. For the GiR configurations, this maximum lifting criteria is not reached; the test was stopped following the failure of the rod in the tensile part.

Regarding the behaviour of samples, the NG-2 and NG-4 tests show an elastic part following by a plastic plateau during which the maximum force is reached at the failure. A ductile failure is observed thanks to the yielding of the steel rod and a brittle failure of the wood is avoided. In the TC tests, the behaviour is not elastic because of the progressive yielding of the metal clamp and pull-out of the screws.

It seems that sinking is not a limiting feature of the test. In fact, at the same force, the TC series shows a sinking approximately 20 times higher than the series with glued-in-rods. There is no wood damage, it is only the rotation at the level of the angle of the clamp. However, only NG-4 shows visible woodwork after the test in the compressed area (Fig. 10). Comparing NG-2 and NG-4, with the same force, NG-2 digs 50% deeper into the wood.

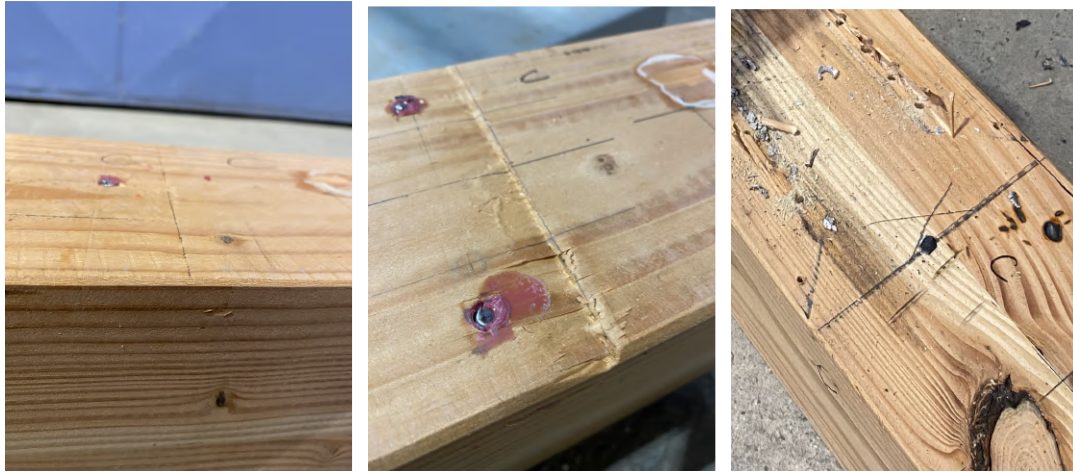


FIGURE 10. Woodwork (NG-2, NG-4 and TC)

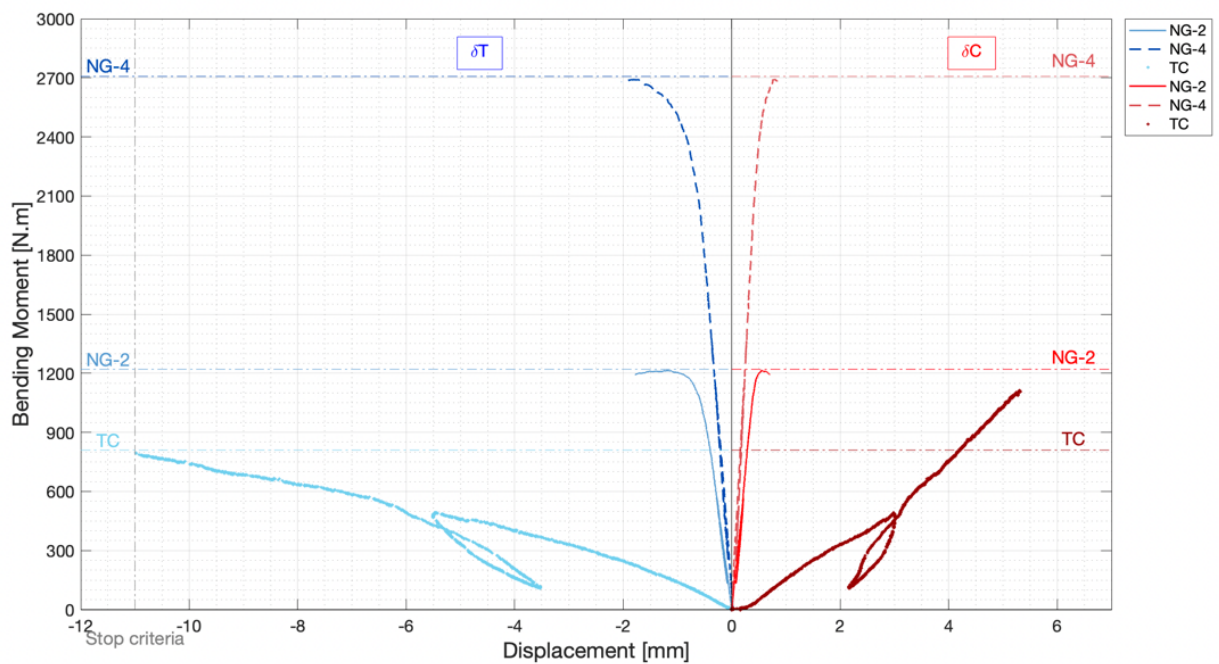


FIGURE 11. Bending Moment VS Lifting and Sinking

The rotation of the connection is determined using the LVDTs C and T, positioned on either side of the joint. The rotation angle of the connection θ is given by Eq. 3 (Fig. 7a):

$$\theta = \frac{(|\delta T| + |\delta C|)}{b_b} \quad (3)$$

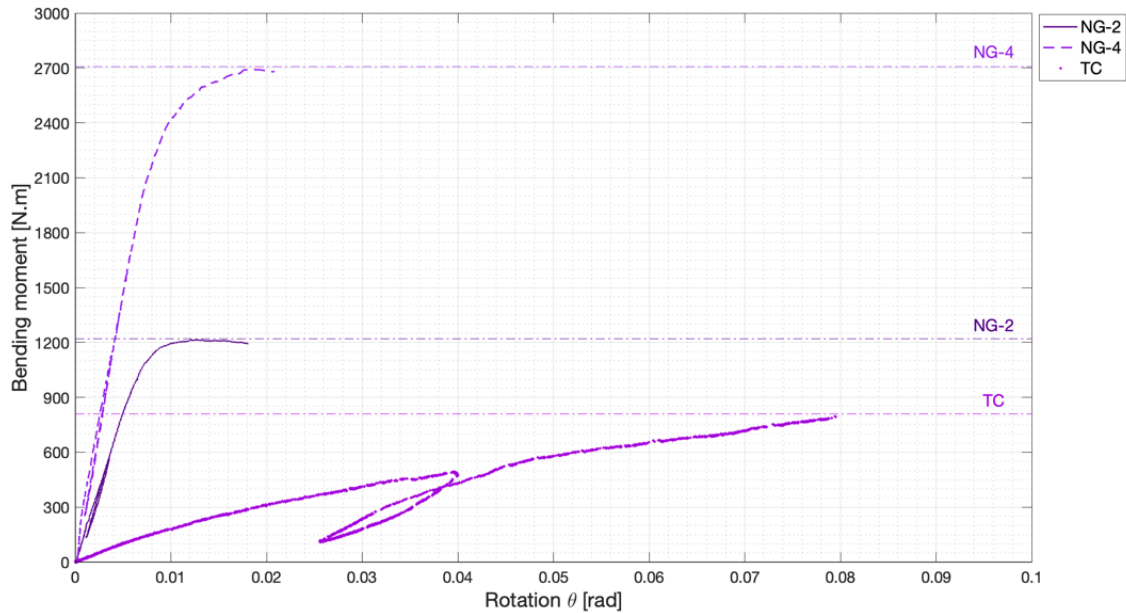


FIGURE 12. Bending Moment VS Rotation

A significant difference in slope, and therefore stiffness is observed between the configurations with GiR (NG-2 and NG-4) and the configuration with the metal clamp (TC). The stiffness of TC is 10 to 15 times lower than with rods. Indeed, TC allows larger deformation than GiR configurations due to the yielding of the metal clamp. Comparing series NG-2 et NG-4, the rotational stiffness almost doubles when the number of rods is increased from 2 to 4 as highlighted in previous studies (Gauthier-Turcotte et al. 2022). Indeed, the stiffness varies from 167,4 kN.m/rad for NG-2 to 283,6 kN.m/rad for NG-4. In Table 2, the plastic angle is lower than 1° for GiR configurations, revealing its high rigidity. If high stiffness is desired, more rods should be used. With a fixed inertia and length, this would increase the stiffness of the connection and therefore make it possible to consider semi-rigid or even rigid connections.

The stiffness, presented as one of the most interesting properties of glued-in-rods connections, is important for the design. Indeed, deflection is constrained by the permitted rotation between the beam and the column; so, deflection depends greatly on the stiffness of the connection. More generally, the value of the deflection under load is an SLS design element to be considered in Eurocode design. Following Eurocode 5, GiR can be classified as a rigid or semi-rigid connection following the number and the diameter of the threaded rod used.

The elongation at the level of the rod in tension ΔL can be calculated by Eq. 4 considering the geometrical characteristics of the joint and the θ rotation (Fig. 7b). The elongation includes the rod strain and the strains of the adhesive and wood surrounding the rod.

$$\Delta L = (b_b - a_{2,t}) \cdot \tan(\theta) - \delta C \quad (4)$$

where:

- $a_{2,t}$: edge distance

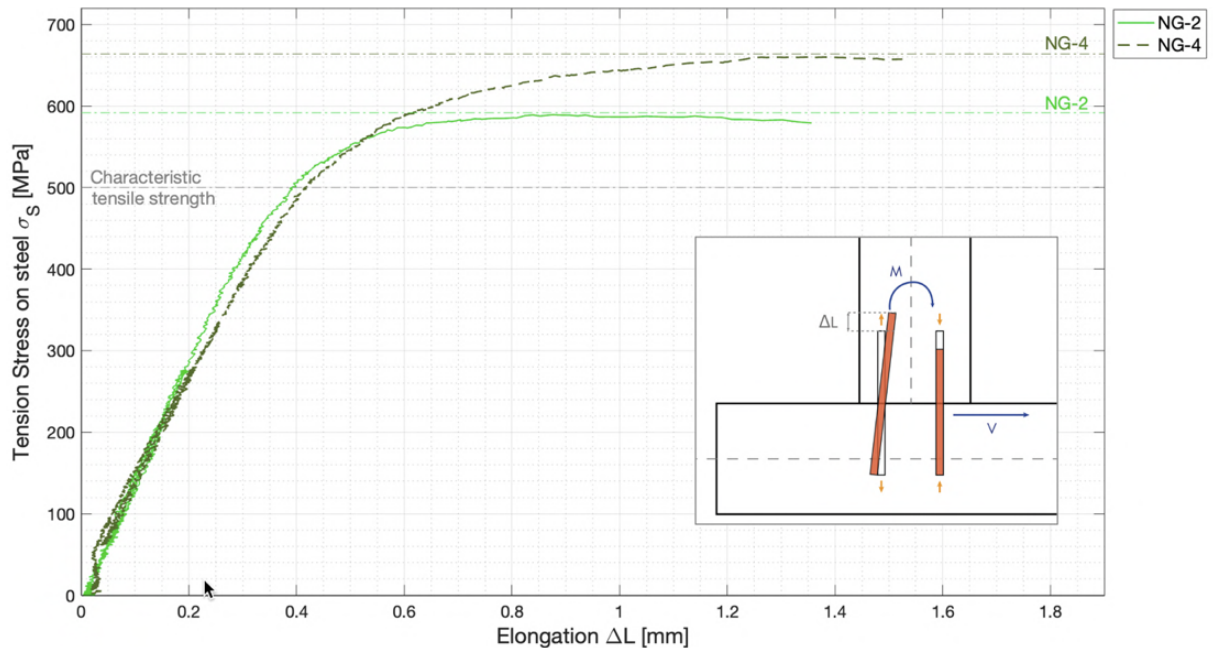


FIGURE 13. Tensions stress on steel VS Elongation of the tensile rod

On Fig. 13, the tensile stress of the rods is represented as a function of this elongation ΔL . The two configurations reach and exceed the characteristic tensile strength of the rod steel (500 MPa).

It can also be noted that the plastic phase of the NG-4 configuration is greater than for the configuration with two rods. The symmetry of the assembly means that it can withstand twice as much stress because the cross-section is doubled.

V. CONCLUSIONS

This research scrutinized the behavior of two series of glued-in rod beam-to-column connections and one series of metal clamp connections. The primary findings can be summarized as follows:

1. The flexural and shear resistance of glued-in-rod connections, when positioned on the same axis, is directly proportional to the number of rods. In other words, doubling the number of rods results in a twofold increase in both the resistances and stiffness of the assembly.
2. The configuration tested revealed that the flexural stiffness of glued-in-rod connections is at least 15 times greater than that of metal clamps, a traditional connection type. Depending on the configuration, glued-in-rod connections can be classified as either rigid or semi-rigid.
3. The glued-in-rod connections demonstrated a ductile failure mode, with the rod yielding in tension, provided that the Eurocode requirements for edge distance and rod spacing are met.

In conclusion, this research highlights the significant potential of glued-in rod technology, particularly in the context of off-site construction, where assembly efficiency and precision are critical. The introduction of a new calculation method within Eurocode 5 enhances the understanding of the performance of these assemblies, enabling their optimized use. Additionally, the substantially higher stiffness of glued-in-rod connections compared to traditional methods paves the way for more robust and durable applications in increasingly sophisticated timber structures.

Future research will investigate the stiffness of glued-in-rod connections. Additionally, the translational stiffness should be addressed. This value could be determined through pull-out tests. Moreover, as of now, Eurocode 5 (2005) does not provide standard verifications for glued-in-rods in timber structures.

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